

AD-A172 233

DYNAMICS OF A LASER-IRRADIATED ADATOM(U) STATE UNIV OF

1/1

NEW YORK AT BUFFALO DEPT OF CHEMISTRY

S VAN SMAALEN ET AL. SEP 86 UBUFFALO/DC/86/TR-13

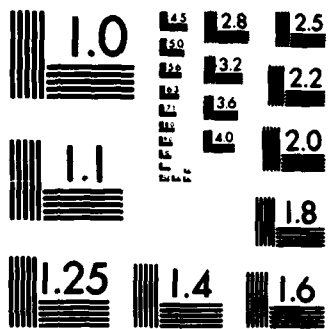
UNCLASSIFIED

N00014-86-K-0043

F/G 7/4

NL





1000

AD-A172 233

(12)

OFFICE OF NAVAL RESEARCH

Contract N00014-86-K-0043

TECHNICAL REPORT No. 13

Dynamics of a Laser-Irradiated Adatom

by

Sander van Smaalen, André Peremans, Henk F. Arnoldus and Thomas F. George

Prepared for Publication

in

Spectrochimica Acta

Proceedings of the International Conference on "Chemistry by IR Lasers"
held in Liblice, Czechoslovakia, September 29 - October 3, 1986

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

September 1986

Reproduction in whole or in part is permitted for any purpose of
the United States Government.

This document has been approved for public release and sale;
its distribution is unlimited.

DTIC
ELECTE
SEP 16 1986
S E D

86 9 16 161

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. REFERENCE MARKING AD-AM72283		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UBUFFALO/DC/86/TR-13			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Depts. Chemistry & Physics State University of New York		6b. OFFICE SYMBOL (If applicable)		7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State and ZIP Code) Fronczak Hall, Amherst Campus Buffalo, New York 14260		7b. ADDRESS (City, State and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research		8b. OFFICE SYMBOL (If applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract N00014-86-K-0043	
8c. ADDRESS (City, State and ZIP Code) Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217		10. SOURCE OF FUNDING NOS.			
		PROGRAM ELEMENT NO.		PROJECT NO.	TASK NO.
					WORK UNIT NO.
11. TITLE Dynamics of a Laser-Irradiated Adatom					
12. PERSONAL AUTHOR(S) Sander van Smaalen, André Peremans, Henk F. Arnoldus and Thomas F. George					
13a. TYPE OF REPORT		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Yr., Mo., Day) September 1986	
				15. PAGE COUNT 6	
16. SUPPLEMENTARY NOTATION Prepared for publication in Spectrochimica Acta Proceedings of the International Conference on "Chemistry by IR Lasers" held in Liblice, Czechoslovakia, September 29 - October 3, 1986					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB. GR.	ADSORBED ATOM LASER-IRRADIATED DYNAMICS		
			NON-PERTURBATIVE THEORY RESONANT HEATING LASER-INDUCED DESORPTION		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) The dynamics of an adsorbed atom irradiated by an IR laser in resonance with a single pair of states of the vibrational adbond is studied. Using a non-perturbative treatment for the laser/adbond interaction, a master equation is derived, which governs the time evolution of the populations of the laser/dressed states of the adbond. The effect of resonant heating and laser-induced desorption, as an example of a possible laser-induced surface process, is discussed. p 4					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input checked="" type="checkbox"/> DTIC USERS <input type="checkbox"/>			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. David L. Nelson			22b. TELEPHONE NUMBER (Include Area Code) (202) 696-4410		22c. OFFICE SYMBOL

Dynamics of a laser-irradiated adatom

Sander van Smaalen, André Peremans,* Henk F. Arnoldus and Thomas F. George

Departments of Physics & Astronomy and Chemistry, 239 Fronczak Hall,
 State University of New York at Buffalo, Buffalo, New York 14260, U.S.A.

Abstract - The dynamics of an adsorbed atom irradiated by an I.R. laser in resonance with a single pair of states of the vibrational adbond is studied. Using a non-perturbative treatment for the laser-adsorb interaction, a master equation is derived, which governs the time evolution of the populations of the laser-dressed states of the adbond. The effect of resonant heating and laser-induced desorption, as an example of a possible laser-induced surface process, is discussed.

INTRODUCTION

It has been realized for quite a time that laser irradiation can affect or induce chemical reactions [1,2]. Combining this with the common knowledge that surfaces, i.e., catalysts, can influence chemical reactions, then opens the interesting possibility of joining the control by lasers and surfaces, in order to manipulate the occurring chemical reactions in greater detail. A quantitative theoretical treatment of a chemical reaction is very involved. However, the first step in a chemical reaction is the formation of an activated complex. The energy necessary for the formation of the complex can be extracted from the translational and vibrational energy of the reactants or added inert species. Here enters one possibility of applying a laser to modify the reaction, since reacting molecules might acquire the necessary energy to become excited to high vibrational or electronic states from the radiation field. Surfaces alter reactions via the induced modifications of the adsorbed species and by the fact that they restrict the motion of the molecules. The role played by a laser in a surface reaction is more complicated than for gas-phase reactions. The radiation may excite the molecule before adsorption, it may excite the substrate, or it may excite the already adsorbed molecule. We shall only consider the latter mechanism.

Detailed comprehension of laser-induced surface reactions starts with the study of the dynamics of a single adsorbed molecule which is illuminated by a strong coherent field. In this paper we shall focus on recent developments in the theory of the dynamics of vibrationally-excited atoms. Topics to be covered are: How can

the laser excite the adatom, which excited states will be populated, and where does the absorbed energy go? Furthermore, the feasibility of laser-induced (resonant) desorption is discussed.

RELAXATION AND COHERENT EXCITATION

We consider an adsorbed atom on a harmonic crystal, irradiated by a laser, which is tuned into resonance with a single pair of levels of the vibrationally bounded atom [3-5]. Only the motion perpendicular to the surface is taken into account, because the lateral motion (migration over the surface) hardly couples to the field. The adbond is represented by its reduced density operator [6]

$$\sigma(t) = \text{Tr } \rho(t) \quad (1)$$

where the trace is over the quantum states of the crystal and over the radiation states. With standard techniques [6,7], it is easy to show that in absence of a laser, the time evolution of the level populations $P(t) = \langle n | \sigma(t) | n \rangle$ is governed by the master equation

$$\frac{d}{dt} P_n(t) = \sum_k (a_{kn} P_k(t) - a_{nk} P_n(t)) \quad (2)$$

where a_{nk} is the rate constant for the transition from level n to level k , and the summation extends over the eigenstates of the adbond. The rate constants are determined by the interaction of the adbond with the substrate. Most extensively studied is the relaxation of the adbond due to the lattice vibrations [3-5]. A transition from state $|n\rangle$ to state $|k\rangle$ is then accompanied by the emission into or the absorption from the substrate of one or

* Aspirant du Fonds National de la Recherche Scientifique, Bruxelles.

more phonons. For one-phonon processes the rate constants are given by [4]

$$a_{nk} = |S_{nk}|^2 f(\omega_{nk}) \quad (3)$$

$$f(\omega_{nk}) = \frac{4\pi^2}{M\hbar} \frac{g(|\omega_{nk}|)}{\omega_{nk}} (\bar{n}(\omega_{nk}) + 1) \quad (4)$$

where $\omega_{nk} = \omega_n - \omega_k$ denotes the transition frequency, M is the mass of a surface atom, $\bar{n}(\omega) = [\exp(\hbar\omega/kT) - 1]^{-1}$, and S_{nk} is the matrix element of the derivative of the adbond potential. The function $g(|\omega_{nk}|)$ is the density of phonon states. For a transition frequency which is larger than the Debye frequency, $g(|\omega_{nk}|)$ is vanishingly small, and multiphonon transitions have to be taken into account [8]. On metals the coupling with electronic transitions in the conduction band provide another possible channel for relaxation [9,10].

The interaction between the laser and the adbond can be treated analogously to the phonon interactions [5], provided that the intensity is not too high. This yields a similar master equation as Eqn. (2). The transition rates then divide into a phonon part (Eqns. (3) and (4)) and a term due to the interaction with the laser, which represents radiative stimulated transitions. The latter only occurs in the rate constants a and a^* for the coupled levels $|g\rangle$ and $|e\rangle$. It is found to be proportional to the laser intensity or, equivalently, to the square of the Rabi frequency

$$\Omega = \hbar^{-1} \underline{\mu} \cdot \underline{E} \quad (5)$$

where $\underline{\mu}$ is the transition-dipole matrix element, and \underline{E} denotes the amplitude and polarization of the electric field of the laser.

The successive approximations involved can easily be studied with the Zwanzig projection technique [7]. For the time evolution of the reduced density matrix we find the exact equation

$$\frac{d\sigma}{dt} = \frac{1}{i\hbar} [H_s, \sigma(t)] - \text{Tr}_b \int_0^t dt' K(t, t') \rho_b \sigma(t-t') \quad (6)$$

where the memory kernel $K(t, t')$ contains the Hamiltonian of the adatom, H_s , the bath, and their interaction. Here ρ_b equals the density matrix of the bath in thermal equilibrium. The first approximation is to retain in $K(t, t')$ only the lowest-order (second-order) terms in the interaction. This is assumed to be accurate for the phonon coupling and is

also expected to be a good approximation for the laser interaction [10]. The second assumption is the Markov approximation [6], which asserts that we can replace $\sigma(t-t')$ by $\sigma(t)$ in Eqn. (6). This can be justified if $\sigma(t)$ does not change much on a timescale on which $K(t, t')$ decays to zero as a function of t' for fixed t . For phonons, this is the characteristic time of the displacement autocorrelation function, which is sufficiently short [11]. For the laser interaction the decay time of $K(t, t')$ is the correlation time of the laser, which is essentially infinite for monochromatic radiation. It was found that for reasonable laser intensities the Markov approximation gives poor results [10]. Then an integrodifferential equation (Eqn. (6)) has to be solved, rather than a master equation.

A non-perturbative approach to the laser-adbond interaction was developed recently [4]. Here the Hamiltonian of the adbond, the laser field and the interaction was diagonalized, and subsequently the phonon damping was taken into account in the usual way. Note that with this alternative treatment the problems with the Markov approximation do not arise. Besides that, the method applies to arbitrary strong irradiances.

Let us denote the eigenstates of the adbond by $|k\rangle$, and in particular by $|g\rangle$ and $|e\rangle$ the two states which are coupled by the laser. Then the eigenstates of the adbond Hamiltonian, the laser field and the interaction are given by $|k\rangle$ for $k \neq e, g$, but $|g\rangle$ and $|e\rangle$ are superposed to yield the so-called laser-dressed states [4,12]. Explicitly we obtain

$$|+\rangle = \sin(\theta/2)|g\rangle + \cos(\theta/2)|e\rangle \quad (7)$$

$$|-\rangle = \cos(\theta/2)|g\rangle - \sin(\theta/2)|e\rangle \quad (8)$$

with $\theta = \arctan(\Omega/\Delta)$ and Δ the detuning of the laser from resonance. Subsequent coupling to the phonon reservoir then results in a master equation for the dressed-state populations. The transition rates assume a more complicated form than given by Eqn. (3). For example, the transition from $|+\rangle$ to $|k\rangle$ with $k \neq e, g$ is given by the rate constant [4]

$$a_{+k} = g_- f(\omega_{+k}) |S_{ek}|^2 + g_+ f(\omega_{+k} - \omega_L) |S_{gk}|^2 \quad (9)$$

with $g_- = \cos^2(\theta/2)$, $g_+ = \sin^2(\theta/2)$, and ω_L is the laser frequency. A particularly transparent interpretation arises if two energy levels are assigned to a single dressed state. Then ω_+ and $\omega_- = \omega_+ - \omega_L$ can be regarded as the eigenvalues of $|+\rangle$, and similarly ω_- and $\omega_+ + \omega_L$ represent the positions of $|-\rangle$, as is illustrated in Fig. 1. The transitions from $|+\rangle$ to $|k\rangle$ then

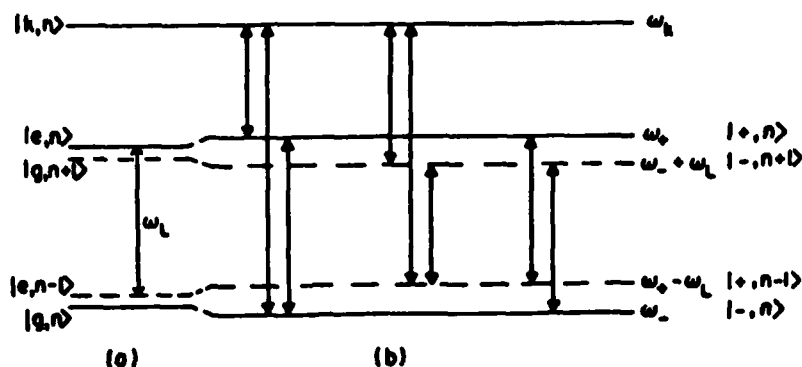


Fig. 1. The energy levels of the adbond plus the laser are represented by the diagram (a) on the left-hand side. The number of photons in the laser mode is indicated by n , and ω_L is the laser frequency. Diagram (b) shows the energy levels of the eigenstates of the adbond and the laser, including the interaction. The adbond states $|g\rangle$ and $|e\rangle$ are then replaced by the dressed states $|+\rangle$ and $|-\rangle$. The occurring phonon transitions are indicated by arrows. The left-most three transitions persist when the laser is turned off. The other transitions occur only in the presence of the laser. Apart from the change in adbond state and in the number of phonons, they also involve the absorption or emission of photons.

contain transitions from level ω_+ to ω_- , and from level $\omega_+ - \omega_L$ to ω_- . The phonon energies involved are exactly the level distances, as depicted in Fig. 1.

Transitions between either one of the levels ω_+ or ω_- and a level ω_k and transitions between ω_+ and ω_- ($k, l = +$ or $-$) survive when the laser is turned off. Hence they can be interpreted as pure-phonon transitions. The additional transitions also require the absorption or emission of photons. For a low intensity the rate constants for these transitions are proportional to the laser power (one-photon process) or its square (two-photon process). For high intensities they assume saturation values, corresponding to the value $\theta = \pm \pi/2$ in the parameterization of the dressed states.

The coherences between the dressed states evolve independently from the populations. It can be shown that they vanish exponentially in time [4]. The inverse of Eqns. (7) and (8) can be used to derive an equation for the populations of the bare states. It then follows that the equations for the populations are coupled to those for the coherences P_{eg} and P_{ge} . This result is different from perturbation theory, which yields a master equation for the bare-level populations, regardless of the time evolution of the coherences.

Sufficiently long after the switch-on of the laser, the system will reach a steady state, for which the reduced density matrix of the adbond remains constant in time. For $dP_{kl}/dt = 0$, the coherences between the bare states can then be eliminated, and a genuine master equation for the bare-level populations arises [4,13]. We find

$$A'_n P_n(-) = \sum_k A'_{kn} P_k(-). \quad (10)$$

Here, $A'_n = \sum_k A'_{nk}$ and $A'_{nk} = A_{nk}$, except for A'_{eg} and A'_{ge} , which are given by

$$A'_{eg} = A_{eg} + \frac{A_+ + A_-}{(A_+ + A_-)^2 + 4\Delta^2} \Omega^2 \quad (11)$$

$$A'_{ge} = A_{ge} + \frac{A_+ + A_-}{(A_+ + A_-)^2 + 4\Delta^2} \Omega^2. \quad (12)$$

Note that in the steady state the Markov approximation for the laser field gives the same result as the non-perturbative approach [10].

ENERGY FLOW

A phonon transition from state $|k\rangle$ to $|l\rangle$ changes the energy of the substrate by an amount of the phonon energy $\hbar|\omega_k|$. Phonon absorption lowers the substrate energy, and phonon emission raises its energy content. In equilibrium (and without a laser) the net energy exchange between the adbond and the substrate is zero. In perturbation theory the laser gives rise to transitions between the two levels $|e\rangle$ and $|g\rangle$. With each transition an energy quantum $\hbar\omega_L$ is exchanged between the laser and the adbond. In the non-perturbative approach the absorption/emission of photons is incorporated in the diagonalization, resulting in the appearance of dressed states, and only the phonon transitions remain explicitly present (Fig. 1).

The populations are time independent in the steady state, as is the adbond energy. The only effect of the transitions between the adbond states is then to carry a net energy flow from the laser into the substrate, a process which is called resonant heating [14]. The energy which is absorbed by the crystal per unit of time is given by [13,15,16]

$$\frac{dW}{dt} = \hbar\omega_L \frac{A_e + A_g}{(A_e + A_g)^2 + 4\Delta^2} \times \Omega^2 (P_g(-) - P_e(-)). \quad (13)$$

For low intensities the populations of $|g\rangle$ and $|e\rangle$ are hardly altered by the radiation, and hence it follows from Eqn. (13) that the energy flow is proportional to the intensity Ω^2 . It can be shown from Eqns. (10) and (13) that the quantity $\Omega^2(P_g(-) - P_e(-))$ becomes independent of Ω^2 , and consequently the energy flow saturates. An upper bound for the energy flow is [15]

$$\frac{dW}{dt} \leq \hbar\omega_L A_e P_e(-) \quad (14)$$

which exhibits the saturation effect. The equality holds in the low-temperature limit.

From expressions (11) and (12) it follows immediately that we can interpret the second terms on the right-hand side as the rate constants a for stimulated photon absorption and emission in the $|e\rangle - |g\rangle$ transition. Then the absorption rate equals $a P_e(-)$, and stimulated emissions, which accompany an $|e\rangle \rightarrow |g\rangle$ transition, occur at a rate $a P_g(-)$. The effective number of transitions from $|g\rangle$ to $|e\rangle$ per unit of time then becomes $a(P_g(-) - P_e(-))$, and multiplication by the photon energy $\hbar\omega_L$ then yields the result (13). This identification elucidates the appearance of the various factors in the expression for dW/dt .

CONCLUSIONS

A theory is presented for the dynamics of an adatom, irradiated by an intense laser, which is in near resonance with a single pair of levels of the vibrational adbond. A master equation for the time evolution of the populations of the laser-dressed states of the reduced density matrix of the adbond is derived. The transitions between the states can be interpreted as phonon transitions between the dressed levels of the adbond. Stimulated radiative transitions are incorporated in the transformation to dressed states.

The phonon transitions between the adbond states give rise to an energy flow from the laser into the substrate. Even in the steady state (where the level populations are time independent) the energy flow assumes a non-zero value. For

low intensities the energy flow is proportional to the laser intensity, whereas for high intensities saturation occurs. This is illustrated by the derivation of an upper bound (Eqn. (14)). It follows that the energy flow is limited by the excited-level population, multiplied by its decay constant. This clearly exhibits that, when the laser is used to maintain the adbond in an excited state, a fast heating of the crystal is inevitable. Moreover, the ratio of the excited-level population and the energy flow (considered as a measure of the efficiency of one process over the other) appears to be independent of the laser power.

To be specific, let us compare the efficiency of a laser-induced surface process and the energy flow. A measure of this is the number of photons which is necessary to sustain the desired process, divided by the number of photons which heat the substrate. As an example we have studied laser-induced desorption [15]. It is found that for low temperatures this ratio is independent of the laser power, and much smaller than unity, indicating that laser-induced (resonant) desorption cannot be expected to be a very efficient process.

Acknowledgments - This research was supported by the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009, the Office of Naval Research, and the National Science Foundation under Grant CHE-8519053. The United States Government is authorized to reproduce and distribute reprints notwithstanding any copyright notation hereon.

REFERENCES

- [1] J.I. Steinfeld, Ed., *Laser-Induced Chemical Processes*, Plenum, New York (1981).
- [2] T.J. Chuang, *Surf. Sci. Rep.* **3**, 1 (1983).
- [3] S. Efrima, C. Jedrzejek, K.F. Freed, E. Hood and H. Metiu, *J. Chem. Phys.* **79**, 2436 (1983).
- [4] H.F. Arnoldus, S. van Smaalen and T.F. George, *Phys. Rev. B*, in press (1986).
- [5] Z.W. Gortel, H.J. Kreuzer, P. Piercy and R. Teshima, *Phys. Rev. B* **27**, 5066 (1983).
- [6] W.H. Louisell, *Quantum Statistical Properties of Radiation*, J. Wiley, New York (1973).
- [7] R.W. Zwanzig, in *Lectures in Theoretical Physics* (edited by W.E. Britten, B.W. Downs and J. Downs), p. 100, Interscience, New York (1961).

- [8] C. Jedrzejek, K.F. Freed, S. Efrima and H. Metiu, Chem. Phys. Lett. 79, 227 (1981).
- [9] B.N.J. Persson and M. Persson, Solid State Commun. 36, 175 (1980).
- [10] A. Peremans, J. Darville, J.M. Gilles and T.F. George, Phys. Rev. B, submitted.
- [11] A.C. Beri and T.F. George, J. Vac. Sci. Technol. B 3, 1529 (1985).
- [12] C. Cohen-Tannoudji and S. Reynaud, J. Phys. B: At. Mol. Phys. 10, 345 (1977).
- [13] S. van Smaalen and T.F. George, Surf. Sci., submitted.
- [14] Z.W. Gortel, H.J. Kreuzer, P. Piercy and R. Teshima, Phys. Rev. B 28, 2119 (1983).
- [15] S. van Smaalen, H.F. Arnoldus and T.F. George, Phys. Rev. B, submitted.
- [16] H.F. Arnoldus and T.F. George, J. Opt. Soc. Am. B, in press (1986).

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



TECHNICAL REPORT DISTRIBUTION LIST, GEN

	<u>No. Copies</u>		<u>No. Copies</u>
Office of Naval Research Attn: Code 413 800 N. Quincy Street Arlington, Virginia 22217	2	Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Dr. Bernard Douda Naval Weapons Support Center Code 5042 Crane, Indiana 47522	1	Naval Weapons Center Attn: Dr. Ron Atkins Chemistry Division China Lake, California 93555	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Washington, D.C. 20360	1	Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, California 93401	1	U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
DTNSRDC Attn: Dr. G. Bosmajian Applied Chemistry Division Annapolis, Maryland 21401	1	Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375	1	Dr. David L. Nelson Chemistry Division Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217	1

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. G. A. Somorjai
Department of Chemistry
University of California
Berkeley, California 94720

Dr. J. Murday
Naval Research Laboratory
Surface Chemistry Division (6170)
455 Overlook Avenue, S.W.
Washington, D.C. 20375

Dr. J. B. Hudson
Materials Division
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Theodore E. Madey
Surface Chemistry Section
Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

Dr. J. E. Demuth
IBM Corporation
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. M. G. Lagally
Department of Metallurgical
and Mining Engineering
University of Wisconsin
Madison, Wisconsin 53706

Dr. R. P. Van Duyne
Chemistry Department
Northwestern University
Evanston, Illinois 60637

Dr. J. M. White
Department of Chemistry
University of Texas
Austin, Texas 78712

Dr. D. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940

Dr. W. Kohn
Department of Physics
University of California, San Diego
La Jolla, California 92037

Dr. R. L. Park
Director, Center of Materials
Research
University of Maryland
College Park, Maryland 20742

Dr. W. T. Peria
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Keith H. Johnson
Department of Metallurgy and
Materials Science
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. S. Sibener
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Arnold Green
Quantum Surface Dynamics Branch
Code 3817
Naval Weapons Center
China Lake, California 93555

Dr. A. Wold
Department of Chemistry
Brown University
Providence, Rhode Island 02912

Dr. S. L. Bernasek
Department of Chemistry
Princeton University
Princeton, New Jersey 08544

Dr. P. Lund
Department of Chemistry
Howard University
Washington, D.C. 20059

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6132
Naval Research Laboratory
Washington, D.C. 20375

Dr. Richard Colton
Code 6112
Naval Research Laboratory
Washington, D.C. 20375

Dr. Dan Pierce
National Bureau of Standards
Optical Physics Division
Washington, D.C. 20234

Dr. R. Stanley Williams
Department of Chemistry
University of California
Los Angeles, California 90024

Dr. R. P. Messmer
Materials Characterization Lab.
General Electric Company
Schenectady, New York 22217

Dr. Robert Gomer
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Ronald Lee
R301
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

Dr. Paul Schoen
Code 5570
Naval Research Laboratory
Washington, D.C. 20375

Dr. John T. Yates
Department of Chemistry
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375

Dr. L. Kesmodel
Department of Physics
Indiana University
Bloomington, Indiana 47403

Dr. K. C. Janda
California Institute of Technology
Division of Chemistry and Chemical
Engineering
Pasadena, California 91125

Dr. E. A. Irene
Department of Chemistry
University of North Carolina
Chapel Hill, North Carolina 27514

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974

Dr. Martin Fleischmann
Department of Chemistry
Southampton University
Southampton SO9 5NH
Hampshire, England

Dr. John W. Wilkins
Cornell University
Laboratory of Atomic and
Solid State Physics
Ithaca, New York 14853

Dr. Richard Smardzewski
Code 6130
Naval Research Laboratory
Washington, D.C. 20375

Dr. H. Tachikawa
Chemistry Department
Jackson State University
Jackson, Mississippi 39217

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. R. G. Wallis
Department of Physics
University of California
Irvine, California 92664

Dr. D. Ramaker
Chemistry Department
George Washington University
Washington, D.C. 20052

Dr. J. C. Hemminger
Chemistry Department
University of California
Irvine, California 92717

Dr. T. F. George
Chemistry Department
University of Rochester
Rochester, New York 14627

Dr. G. Rubloff
IBM
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. Horia Metiu
Chemistry Department
University of California
Santa Barbara, California 93106

Dr. W. Goddard
Division of Chemistry
California Institute of Technology
Pasadena, California 91125

Dr. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

Dr. R. W. Plummer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 41106

Dr. N. Winograd
Department of Chemistry
Pennsylvania State University
University Park, Pennsylvania 16802

Dr. Roald Hoffmann
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. A. Steckl
Department of Electrical and
Systems Engineering
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. G. H. Morrison
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. P. Hansma
Physics Department
University of California
Santa Barbara, California 93106

Dr. J. Baldeschwieler
California Institute of Technology
Division of Chemistry
Pasadena, California 91125

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. J. E. Jensen
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. J. H. Weaver
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minnesota 55455

Dr. W. Goddard
Division of Chemistry
California Institute of Technology
Pasadena, California 91125

Dr. A. Reisman
Microelectronics Center of North Carolina
Research Triangle Park, North Carolina
27709

Dr. M. Grunze
Laboratory for Surface Science and
Technology
University of Maine
Orono, Maine 04469

Dr. J. Butler
Naval Research Laboratory
Code 6115
Washington D.C. 20375

Dr. L. Interante
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Irvin Heard
Chemistry and Physics Department
Lincoln University
Lincoln University, Pennsylvania 19352

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506

Dr. W. Knauer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. C. B. Harris
Department of Chemistry
University of California
Berkeley, California 94720

Dr. F. Kutzler
Department of Chemistry
Box 5055
Tennessee Technological University
Cookeville, Tennessee 38501

Dr. D. DiLella
Chemistry Department
George Washington University
Washington D.C. 20052

Dr. R. Reeves
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

END

10-86

DTIC